

Missing States  
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Equation of State  
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Perfect Fluidity  
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Chemical Equilibrium  
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Outlook  
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Backups

# Implications of missing (Hagedorn States) resonances in Heavy-Ion Collisions

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# Outline

- 1 Missing States
- 2 Equation of State
- 3 Perfect Fluidity
- 4 Chemical Equilibrium
- 5 Outlook

# Maximum Temperature of Matter?

- In the 1960's Hagedorn suggested that matter has a maximum temperature, now known as the **Hagedorn Temperature**
- Instead of  $\uparrow$  temperature, heavier particles are created

## Hagedorn States

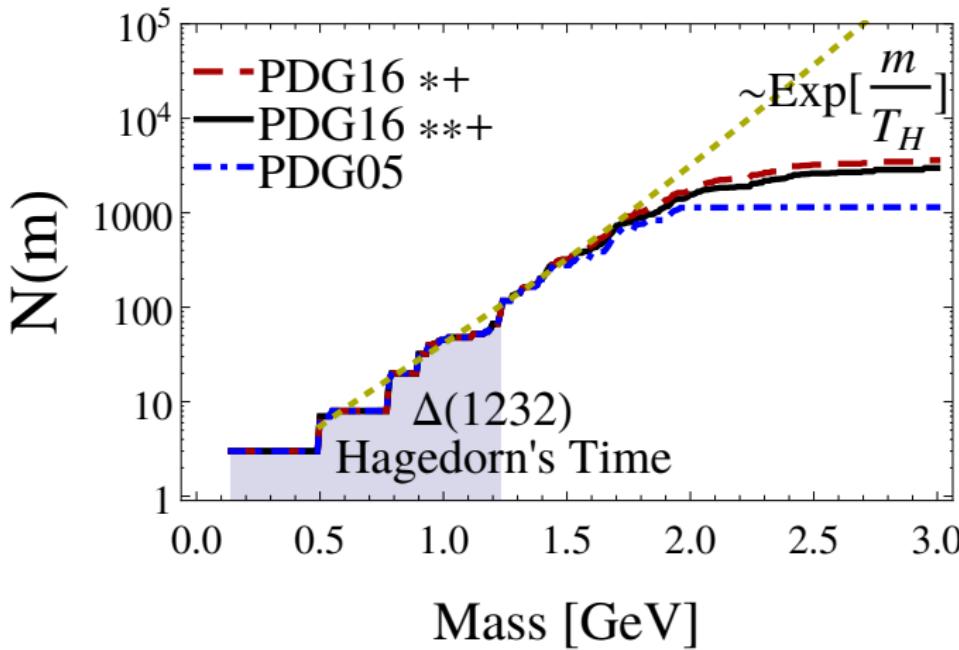
"fireballs consist of fireballs, which consist of fireballs..."



Rolf Hagedorn

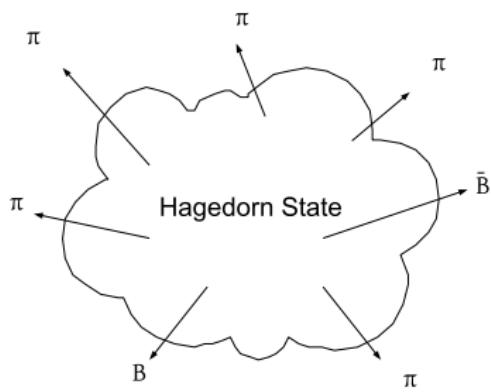
# Connecting Old and New Ideas

- Counting up the resonances  $N(m) = \sum_i d_i \Theta(m - m_i)$  gives exponential mass spectrum  $\sim e^{m/T_H}$



See also Broniowski, Florkowski, Góźdz, PRD70, 117503 (2004); Lo et al. Phys. Rev. C92 (2015) no.5, 055206

# What if we're missing massive states?



If we're missing resonances, then they are probably:

- Heavier than most of the resonances in the Particle Data Booklet
- Have a large decay widths
- Decay into many daughters

Taking Hagedorn's assumption, they have an exponentially increasing mass spectrum

# Modeling their Degeneracy

## Degeneracy of Hagedorn states

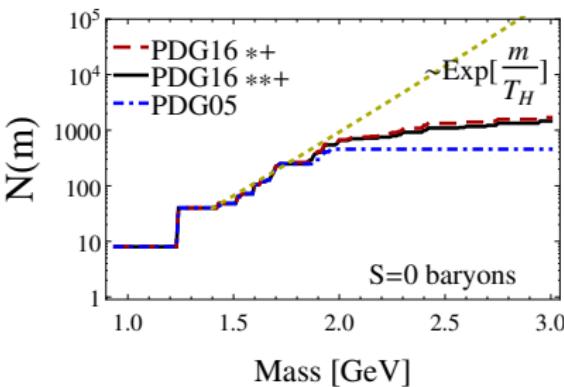
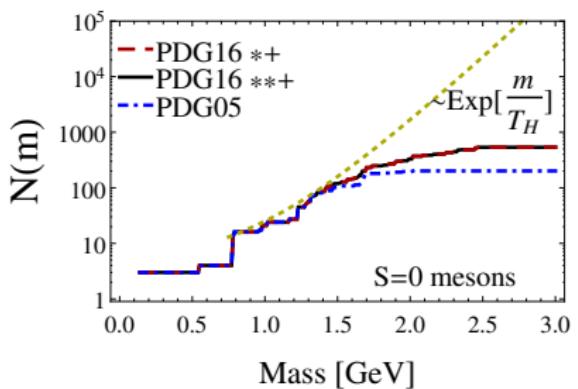
$$\rho(M) = \int_{M_0}^M \frac{A}{[m^2 + (m_0)^2]^a} e^{\frac{m}{T_H}} dm \quad (1)$$

- $a = 3/2$ , decay into 2 daughters\*
- $a = 5/4$ , decay into 2+ daughters
- $a = 0$ , ???

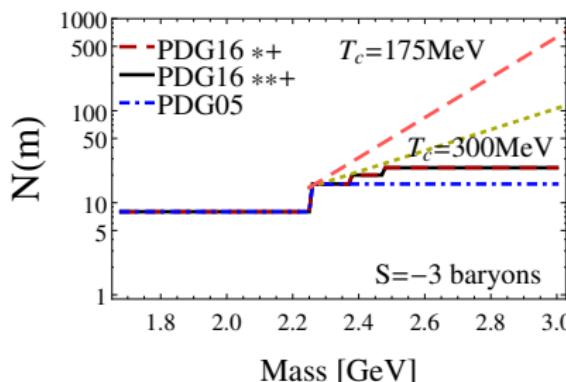
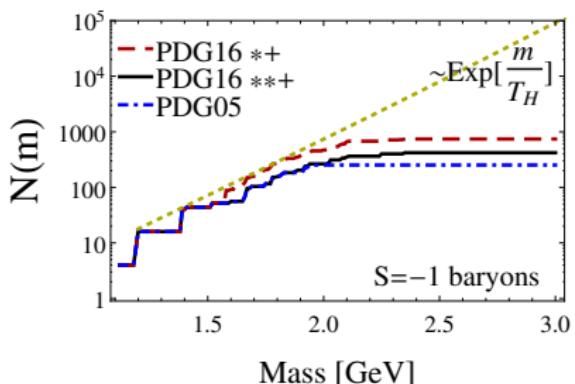
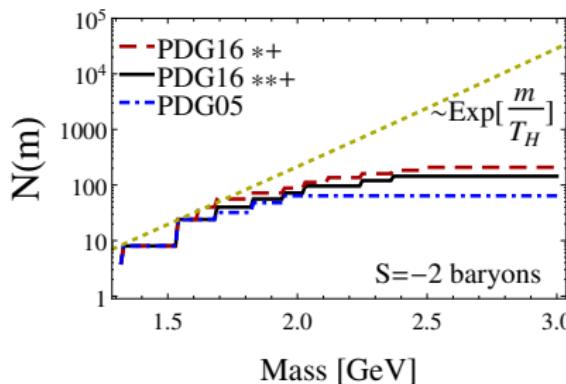
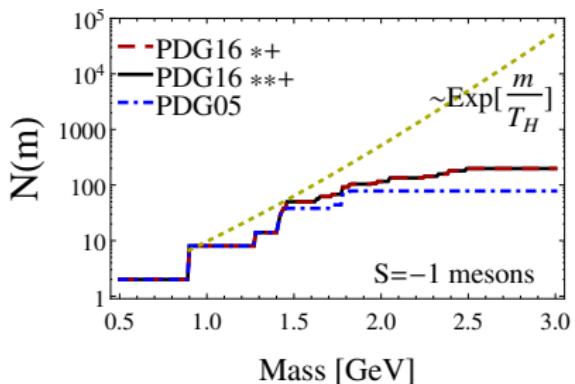
\*Most likely, according to Frautschi PRD3(1971)2821-2834  
See JNH, et. all, PRC86(2012)024913 , PRC81 (2010) 054909 ,  
PRL103(2009)172302 , PRL 100, 252301 (2008) and Majumder & Muller  
2010

# Light Mesons and Baryons

Assuming  $T_H \sim T_c \sim 155$  MeV



# Strange mesons and baryons $T_H \sim T_c \sim 175$ MeV



# Thermodynamic Quantities of Hagedorn States

Hadron Resonance Gas: assumes that interacting hadronic matter in the ground state  $\sim$  non-interacting resonance gas

$$p/T^4 = \frac{1}{VT^3} \left[ \sum_i^{PDG} \ln Z_i + \sum_{bsq} \int_{m0(bsq)}^{\infty} dm \ln Z_{bsq}^{HS}(m) \right]$$

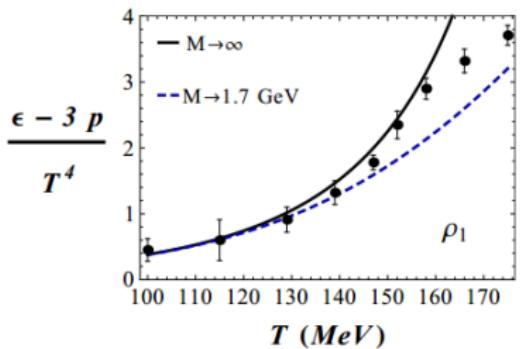
such that

$$\ln Z_i^{PDG} \simeq \frac{d_i}{2\pi^2} \left( \frac{m_i}{T} \right)^2 \sum_{k=1}^{\infty} \frac{(\pm 1)^{k+1}}{k^2} K_2 \left( \frac{km_i}{T} \right) \cosh \left[ \frac{k(B_i \mu_B + S_i \mu_S + Q_i \mu_Q)}{T} \right]$$

$$\ln Z_{bsq}^{HS}(m) \simeq \frac{\rho(m)}{2\pi^2} \left( \frac{m}{T} \right)^2 \sum_{k=1}^{\infty} \frac{(\pm 1)^{k+1}}{k^2} K_2 \left( \frac{km}{T} \right) \cosh \left[ \frac{k(b \mu_B + s \mu_S + q \mu_Q)}{T} \right]$$

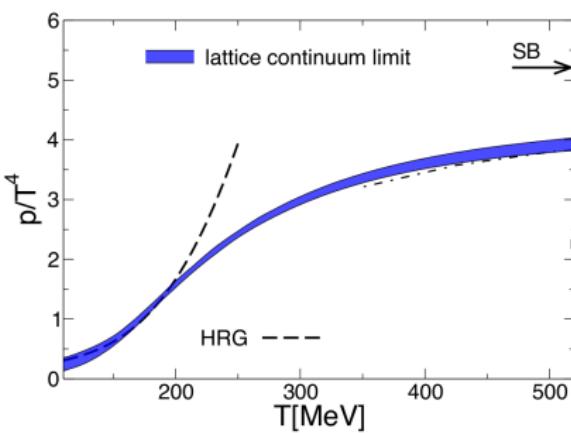
# Comparisons with Lattice QCD

Until  $\sim$  PDG2014, extra resonances were needed to match the Lattice QCD Equation of State **See C. Ratti's Talk**



JNH, Jorge Noronha, Carsten Greiner PRC86 (2012)  
024913

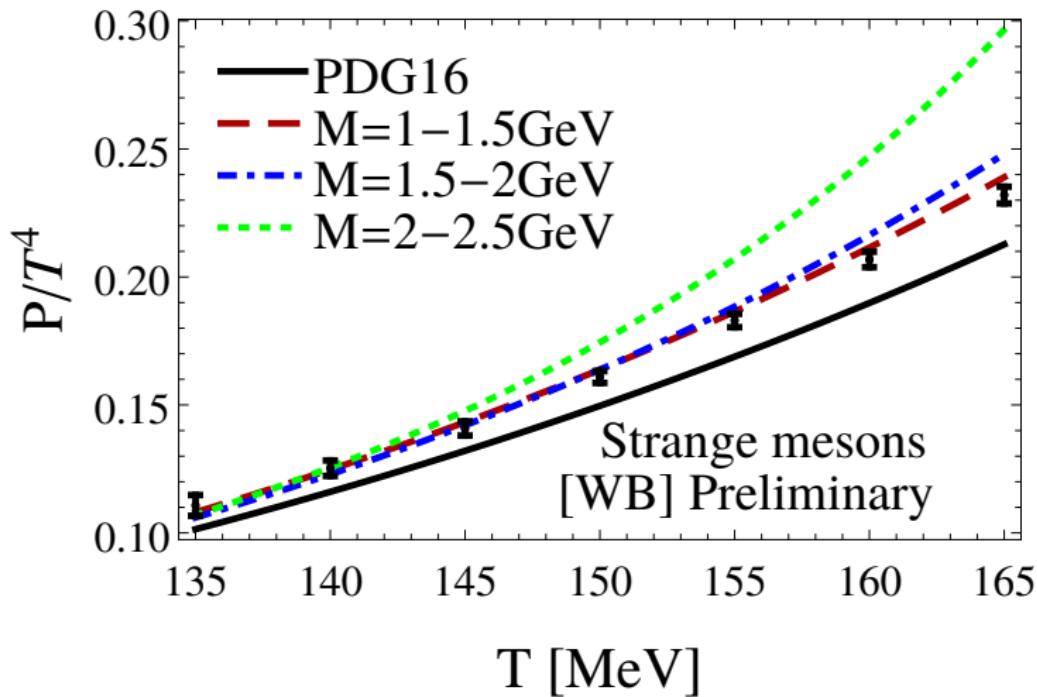
see also JNH et al, PRC81(2010)054909,Majumder & Muller PRL105(2010)252002



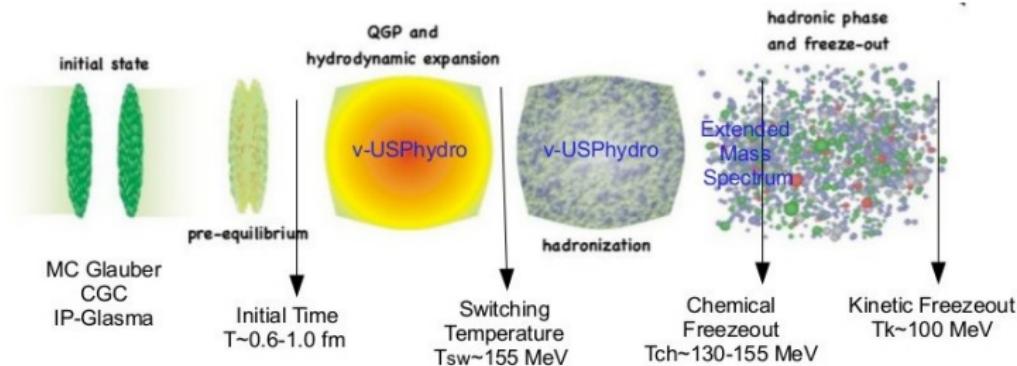
WB Collaboration Phys.Lett. B730 (2014) 99-104

# Comparing Strange Mesons to Lattice QCD

Using Hagedorn states to estimate the mass range difference between Lattice QCD and the PDG16 \*-\*\*\*\*



# From quarks and gluons to fat hadrons

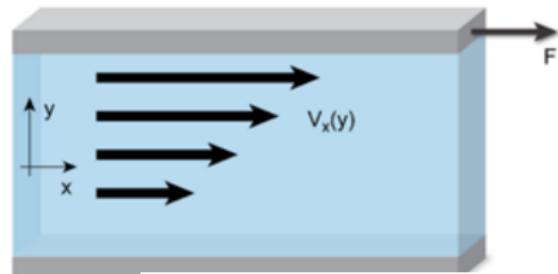


- The Quark Gluon Plasma is the smallest, hottest, and fastest moving liquid on Earth
- Cannot observe the QGP directly, work back from hadrons
- Dynamics of the hadrons are also extremely important!

# Perfect Fluidity Part I

Shear viscosity - Resistance against the deformation of a fluid

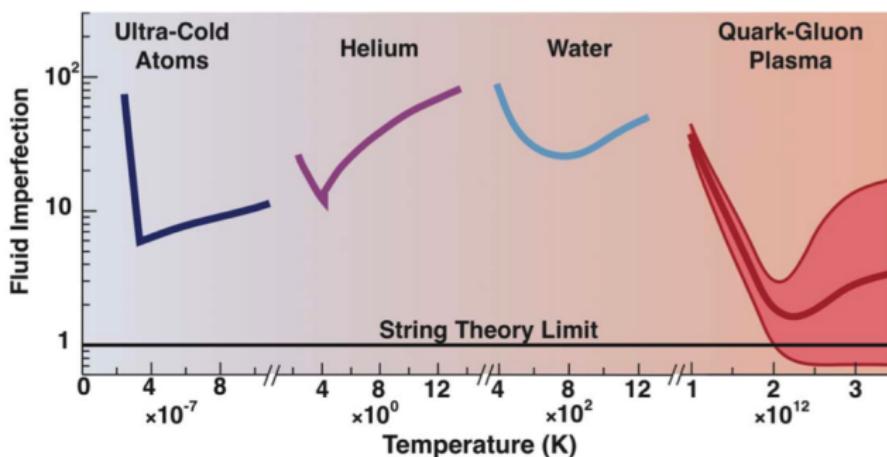
Physics 101



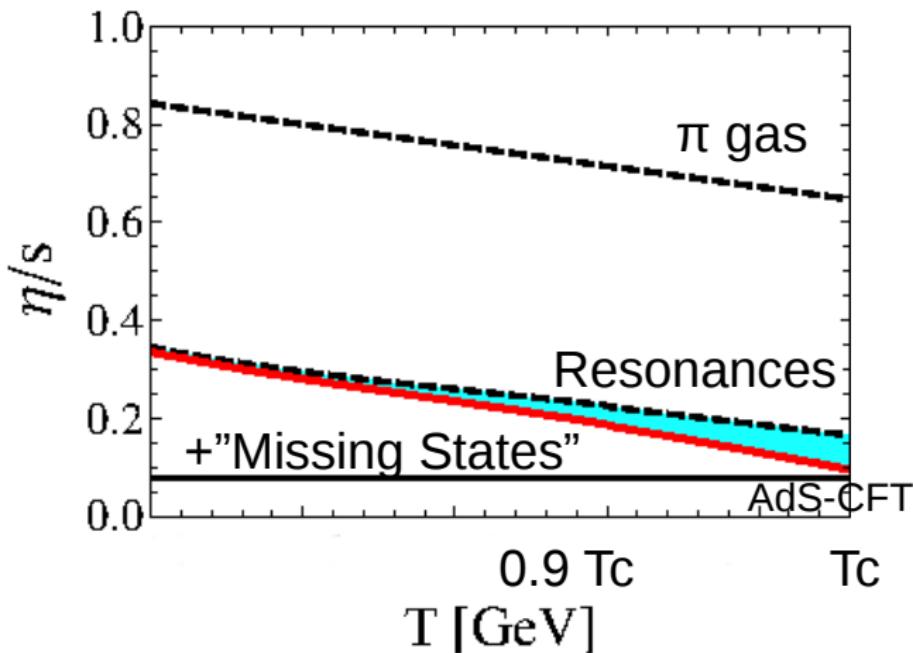
$$\frac{F}{A} = \eta \partial_y v_x(y)$$

For a dilute gas → kinetic theory

$$\eta \sim \frac{1}{3} \sum_i n_i \langle p \rangle_i l_{mfp}$$



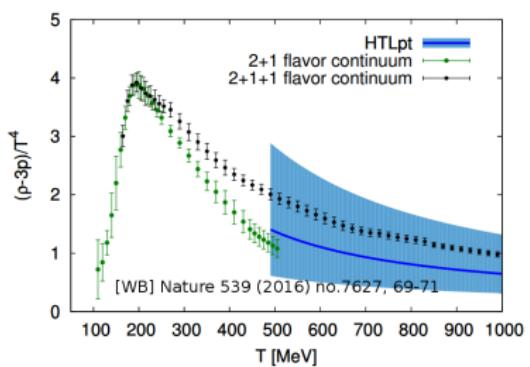
# Perfect Fluidity Part II



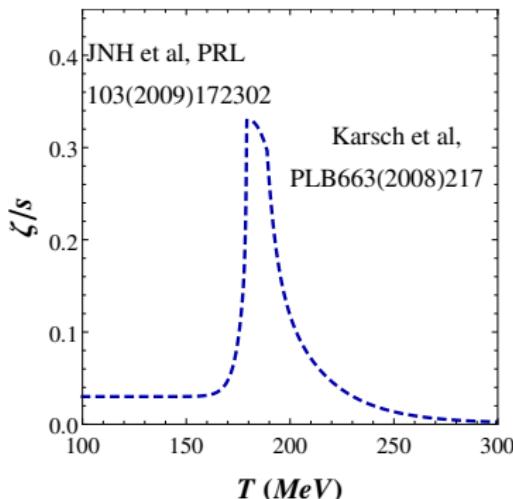
JNH, Noronha, Greiner PRL103(2009)172302; PRC86(2012)024913; Kadam, Mishra NPA934(2014)133-147; Pal PLB684(2010)211-215

# Bulk Viscosity

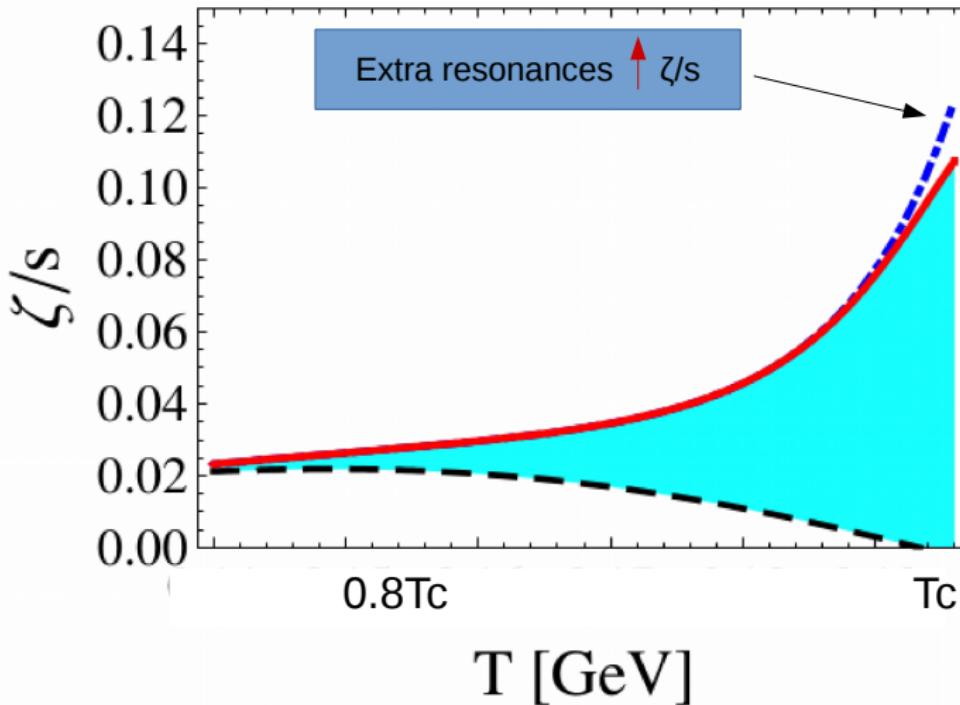
Bulk viscosity - against the radial expansion or compression of a fluid



$$\zeta/s \sim \frac{(T\partial_T - 4)(\varepsilon - 3p)}{(9\omega_0 s)}$$



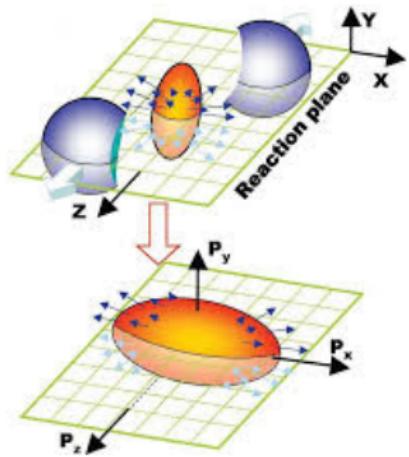
# Bulk Viscosity with extra resonances



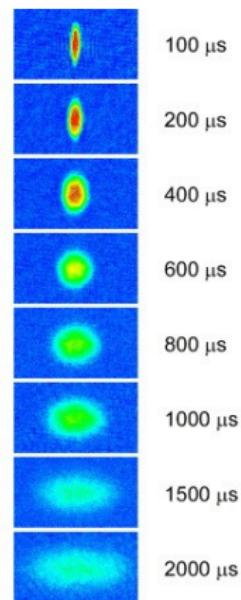
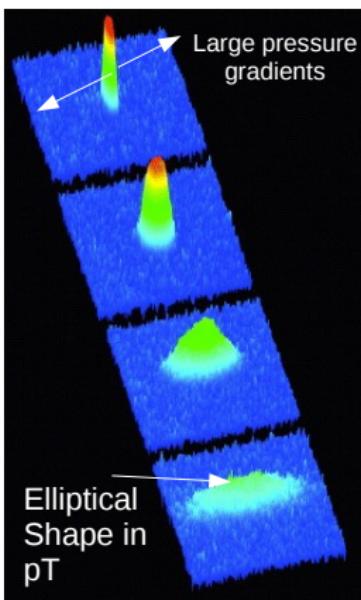
JNH, Noronha, Greiner PRL103(2009)172302; PRC86(2012)024913; Kadam, Mishra NPA934(2014)133-147; Pal PLB684(2010)211-215

# Perfect fluid leads to elliptical flow

Assuming Gold ions are spheres...

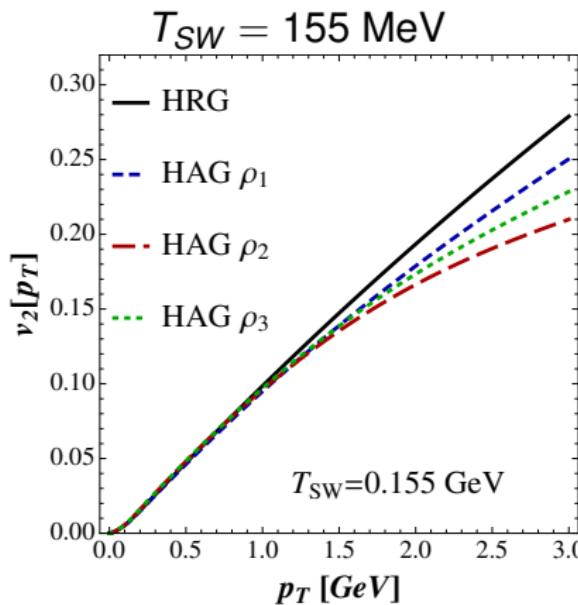
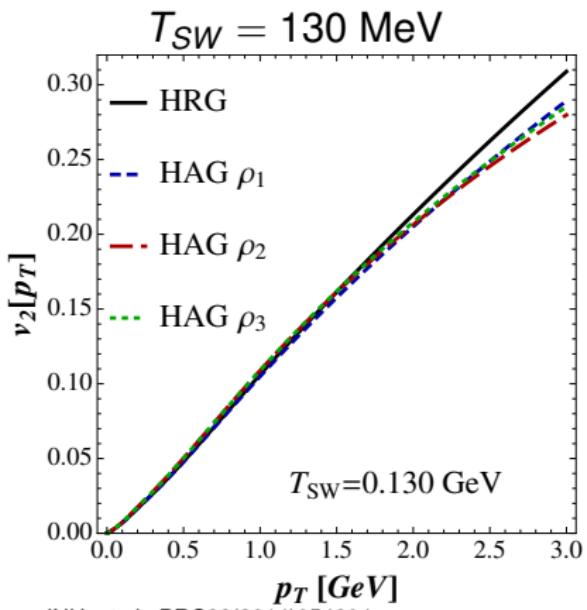


Cold Atoms

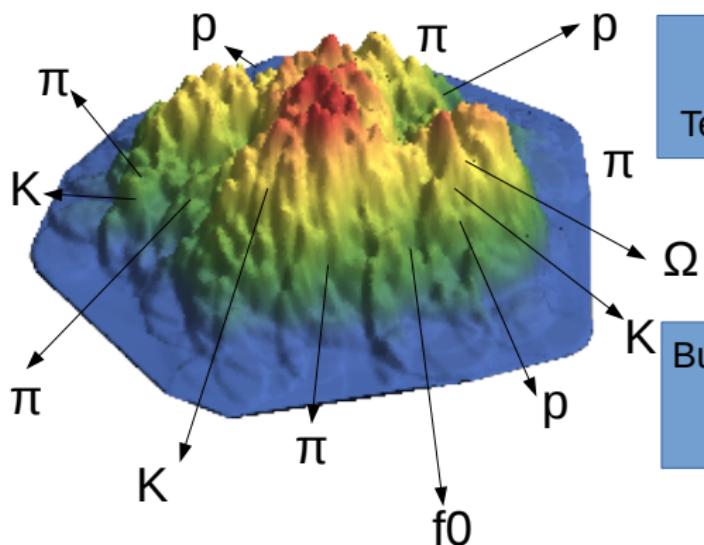


# Extended Mass spectrum and Elliptical Flow

Higher switching temperatures, mean larger effect from HS.



# How long do hadrons take to equilibrate?

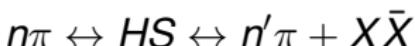


Assume hadrons are emitted at a set Temperature,  $T_{sw} \sim 155$  MeV



But, the surface fluctuations and the hadrons are out-of-equilibrium

# Hagedorn states to “feed” decays



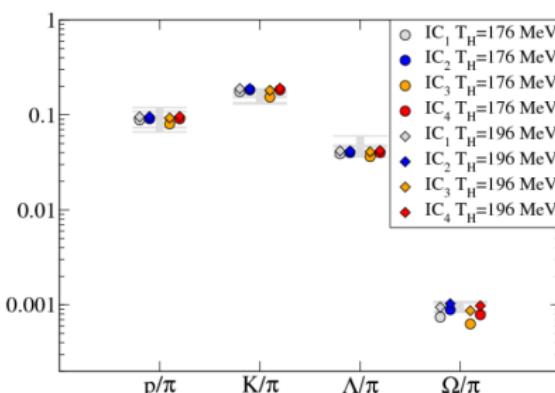
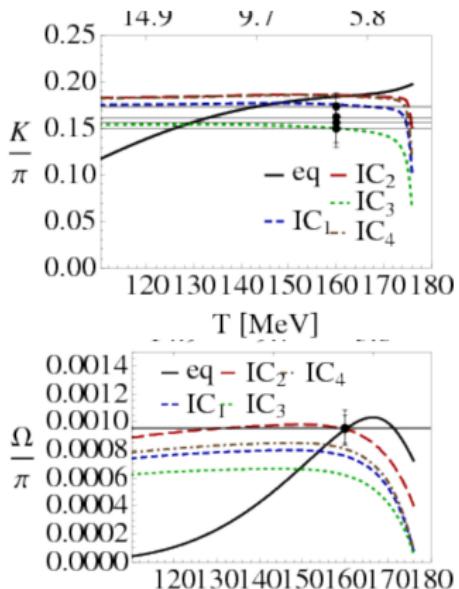
where  $X = p, K, \Lambda, \Xi, \Omega$ 's

- Decays width  $\Gamma(m, X)$  depend on mass and reaction
- Branching Ratios are taking from a micro-canonical model  
Liu, et.al. PRC68(2003)024905, JPG30(2004)S589, PRC69(2004)054002
- Bjorken Expansion 1+1 Dimensions is assumed
- Rate equations (within a cooling, expanding fireball) used to allow for multi-particle reactions
- Only non-strange, mesonic Hagedorn States considered

Model details: JNH et al, arXiv:1405.7298 ; Nucl.Phys. A931 (2014) 1108-1113 ; Phys.Rev. C81 (2010) 054909 ; Phys.Rev. C82 (2010) 024913 ; Phys.Rev.Lett. 100 (2008) 252301

# Hadrons reaching equilibrium dynamically

Varying initial conditions, Hagedorn state parameters etc  
matches experimental particle ratios from RHIC



For rescattering discussion see  
Takeuchi Phys. Rev. C92 (2015)  
no.4, 044907

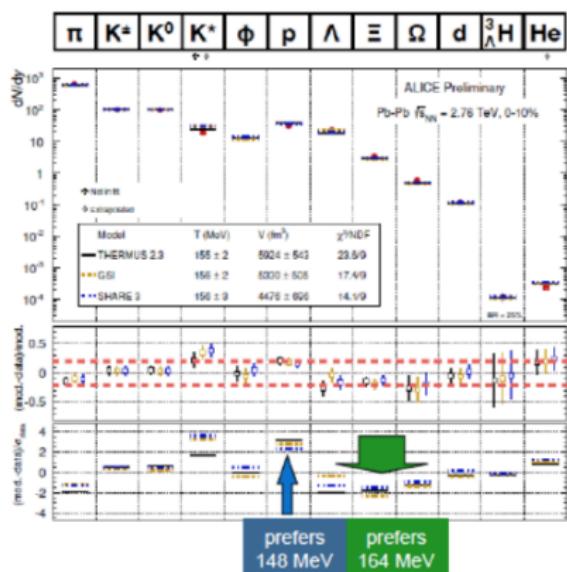
JNH et al, Phys. Rev. C82 (2010) 024913

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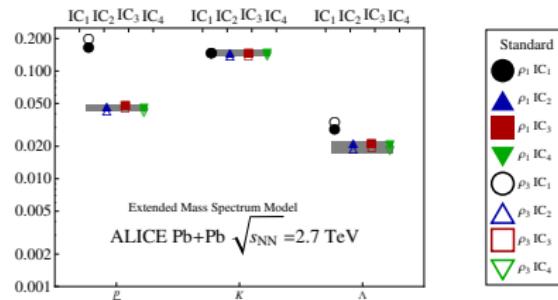
# Thermal fits at RHIC vs. LHC

## LHC $p/\pi$ puzzle

Thermal Fits overpredict  $p/\pi$



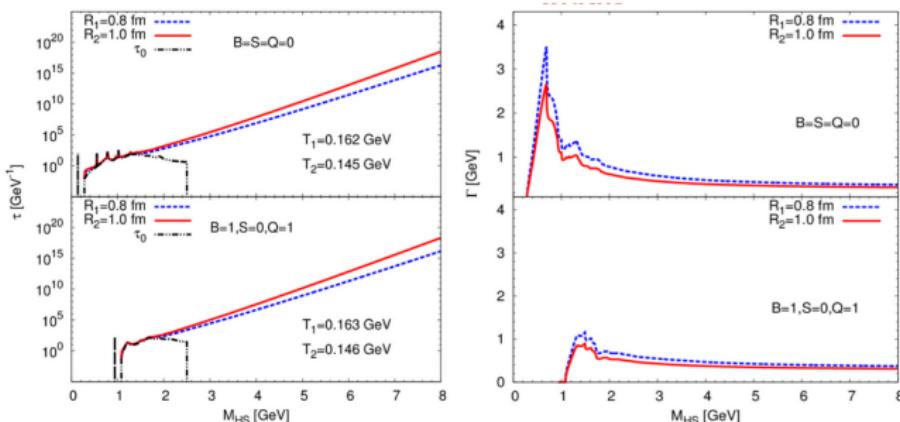
Heavy resonances produce multiple pions,  $\downarrow$  the  $p/\pi$  ratio



JNH and Greiner Nucl.Phys. A931 (2014) 1108-1113 and arXiv:1405.7298

Further discussion: See  
Claudia Ratti's talk

# The Future: Extended Mass Spectrum in Transport



Beitel, Gallmeister, and Greiner Phys.Rev. C90 (2014) no.4, 045203

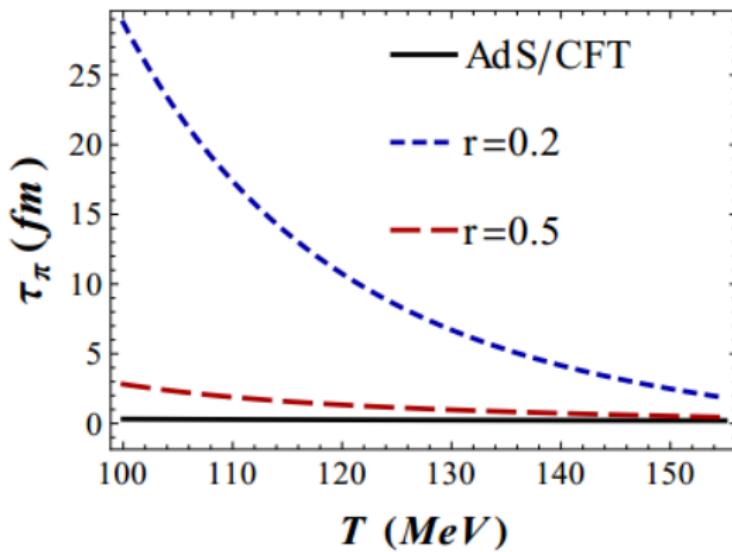
- Allows for resonance input, depends on mass, baryon number, strangeness, and charge.
- Includes all resonance decays.
- Finds that the Hagedorn temperature is the same for mesons and baryons, matches well with known hadrons

# Interface between Spectroscopy and Heavy-ions

If there are missing resonances, it would systematically affect most theory to experiment comparisons in heavy-ion collisions

- Most models in heavy-ions have a standardized hadron cocktail that they read in (includes particle ID, mass, degeneracy, quantum numbers, decay width, and branching ratios)
- These lists can be easily used to make direct comparison between the Hadron Resonance Gas and Lattice QCD
- Needed for dynamical models and thermal fits
- Can a database be created for easy comparisons with the most up-to-date PDG list vs. Quark Models?

# Relaxation time



JNH, Jorge Noronha, Carsten Greiner PRC86(2012)024913 and PRL103(2009)172302

# Rate Equations for the Chem. Eq. Time of Hadrons



$$\frac{d\lambda_i}{dt} = \Gamma_{i,\pi} \left( \sum_n^\infty B_{i,n} \lambda_\pi^n - \lambda_i \right) + \Gamma_{i,X\bar{X}} \left( \lambda_\pi^{\langle n_{i,x} \rangle} \lambda_{X\bar{X}}^2 - \lambda_i \right),$$

$$\begin{aligned} \frac{d\lambda_\pi}{dt} &= \sum_i \Gamma_{i,\pi} \frac{N_i^{eq}}{N_\pi^{eq}} \left( \lambda_i \langle n_i \rangle - \sum_n^\infty B_{i,n} n \lambda_\pi^n \right) \\ &\quad + \sum_i \Gamma_{i,X\bar{X}} \langle n_{i,x} \rangle \frac{N_i^{eq}}{N_\pi^{eq}} \left( \lambda_i - \lambda_\pi^{\langle n_{i,x} \rangle} \lambda_{X\bar{X}}^2 \right), \end{aligned}$$

$$\frac{d\lambda_{X\bar{X}}}{dt} = \sum_i \Gamma_{i,X\bar{X}} \frac{N_i^{eq}}{N_{X\bar{X}}^{eq}} \left( \lambda_i - \lambda_\pi^{\langle n_{i,x} \rangle} \lambda_{X\bar{X}}^2 \right)$$

$\lambda = \frac{N}{N^{eq}}$ ,  $N$  is the total number of each particle, its equilibrium value is  $N^{eq}$ .  $\pi$ 's and  $HS$  begin in chemical equilibrium  
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# Hydrodynamical Expansion

Use an isentropic expansion...

Find  $T(t)$  for the 5% most central collisions

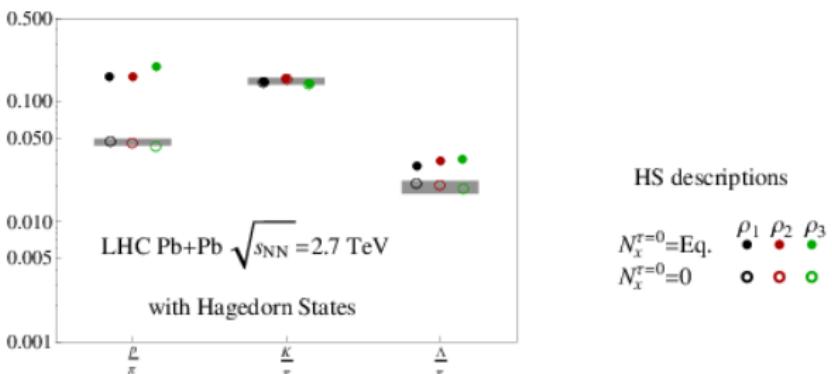
$$\frac{S_\pi}{N_\pi} \int \frac{dN_\pi}{dy} dy = s(T) V(\tau) = \text{const.}$$

## Volume

$$V_{\text{eff}}(\tau \geq \tau_0) = \pi \tau \left( r_0 + v_0(\tau - \tau_0) + .5a_0(\tau - \tau_0)^2 \right)^2$$

- $\tau_0 = 0.6$  and  $1.0$  fm for LHC and RHIC, respectively.
- Begin resonance decays at  $T_{sw} = 155$  MeV
- $T_{end}$  varies on Hagedorn State description

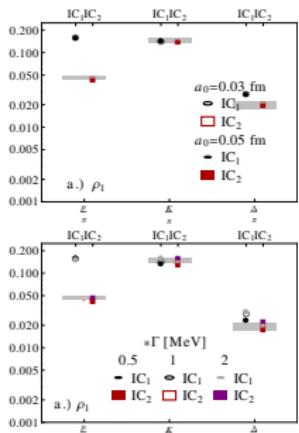
# Results: Extended mass spectrum fits the low $p/\pi$ at ALICE



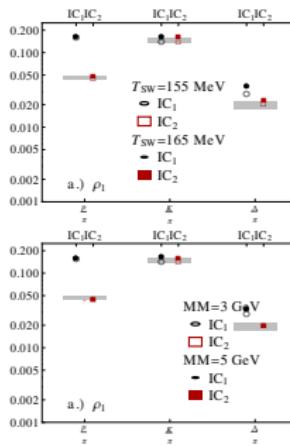
JNH and C. Greiner- to appear shortly

- Initially unpopulated p, K, and  $\Lambda$ 's fit experimental data.
- When all hadrons begin in chem. eq. there is an overpopulation of p's!
- $T_{end} = 133, 136, \text{ and } 128 \text{ MeV}$  for  $\rho_1-\rho_3$ , respectively
- The hydro expansion is significantly shorter at RHIC ( $\Delta\tau \approx 5 \text{ fm}$  vs.  $\Delta\tau \approx 10 \text{ fm}$  at LHC) whereas the time in the hadron resonance gas phase is roughly the same ( $\Delta\tau \approx 4 - 6 \text{ fm}$ ).

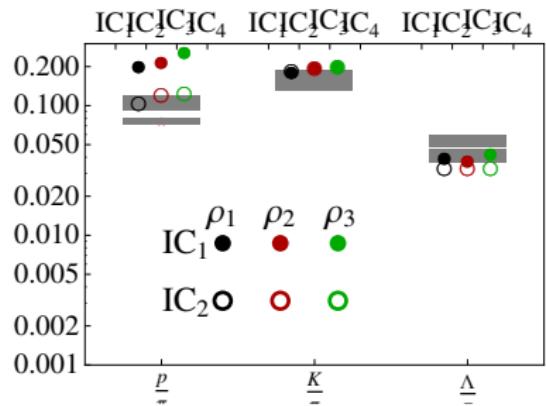
# Results: Hagedorn States fits are robust



JNH and C. Greiner- to appear shortly



# Results: RHIC



- Slightly different setup as previous work but still matches data well
- May indicate a non-zero number of  $\Lambda$ 's or that strange and/or baryonic Hagedorn states are needed

# Otherwork on resonances

- Strangeness enhancement: P. Koch, B. Muller, and J. Rafelski
- $\bar{p} + N \leftrightarrow n\pi$  at SPS: R. Rapp and E. Shuryak
- Anti-hyperons at SPS: C. Greiner and S. Leupold.

# Contribution of HS to Chemical Equilibrium Values

Effective  $X = p, K, \text{ or } \Lambda$

$$\tilde{N}_X = N_X + \sum_i N_i \langle X_i \rangle$$

Effective  $\pi$ 's

$$\tilde{N}_\pi = N_\pi + \sum_i N_i \langle n_i \rangle$$

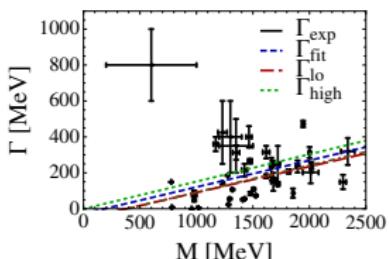
$\langle X_i \rangle$  and  $\langle n_i \rangle$  are calculated  
within a microcanonical model

Liu, et.al. PRC68(2003)024905,  
JPG30(2004)S589, PRC69(2004)054002

# Decay Width

- Linear fit (PDG)

$$\begin{aligned}\Gamma_i &= 0.15m_i - 58 \\ &= 250 - 1000 \text{ MeV}\end{aligned}$$



- $X\bar{X}$  (microcanonical)

$$\Gamma_{i,X\bar{X}} = \langle X \rangle \Gamma_i$$

C. Greiner et al., J.Phys.G31:S725-S732,2005.

$$\Gamma_{i,\pi} = \Gamma_i - \Gamma_{i,X\bar{X}}$$

$$\langle B \rangle \approx 0.06 \text{ to } 0.4$$

$$\langle K \rangle \approx 0.4 \text{ to } 0.5$$

$$\langle \Lambda \rangle \approx 0.01 \text{ to } 0.2$$

# Branching Ratios

- Branching ratios for  $n\pi \leftrightarrow HS$  are described by a Gaussian distribution

$$B_{i,n} \approx \frac{1}{\sigma_i \sqrt{2\pi}} e^{-\frac{(n - \langle n_i \rangle)^2}{2\sigma_i^2}}$$

- Average pion number (Liu, Werner, Aichelin, Phys. Rev. C 68, 024905 (2003).)

$$\langle n_i \rangle = 0.9 + 1.2 \frac{m_i}{m_p}$$

- Standard deviation

$$\sigma_i^2 = (0.5 \frac{m_i}{m_p})^2$$

- After cutoff  $n \geq 2$ ,  $\langle n_i \rangle \approx 3$  to 9 and  $\sigma_i^2 \approx 0.8$  to 11
- For  $HS \leftrightarrow n'\pi + X\bar{X}$ ,  $\langle n_{i,x} \rangle = 2 - 4$
- assume  $\langle n_{i,p} \rangle = 2 \langle n_{i,k} \rangle$